

DELAYED GeV EMISSION FROM COSMOLOGICAL GAMMA-RAY BURSTS : Impact of a Relativistic Wind on External Matter

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Abstract

Sudden collapse of a compact object, or coalescence of a compact binary, can generate an unsteady relativistic wind that lasts for a few seconds. The wind is likely to carry a high magnetic field; and its Lorentz factor depends on the extent to which it is 'loaded' with baryons. If the Lorentz factor is ~ 100 , internal dissipation and shocks in this wind produce a non-thermal gamma-ray burst, detectable in the range $0.1 \text{ MeV} \lesssim E_\gamma \lesssim 0.1 - 1 \text{ GeV}$ out to cosmological distances. The cooled wind ejecta would subsequently be decelerated by the external medium. The resultant blast wave and reverse shock can then give rise to a second burst component, mainly detectable in the GeV range, with a time delay relative to the MeV burst ranging from minutes to hours.

1. Introduction

Emission at energies in the GeV range has been recently reported in a gamma-ray burst (GRB) from EGRET observations (Mukherjee, *et al.*, 1994), continuing to arrive up to ~ 1 hour after the MeV-band emission detected by BATSE within 0.5° of the GeV location. Previous reports of GeV emission, e.g. from the 'Superbowl' burst (Dingus, *et al.*, 1994) also showed a (relatively shorter) delay respect to the MeV burst. A 'simple' fireball model would have problems in explaining these delayed bursts, whether galactic or cosmological, because most of the energy would escape in a single, very short burst when the fireball becomes optically thin. In previous papers we have explored various 'non-simple' fireball and wind models which avoid the problems encountered in the pre-1992 simple models (Mészáros and Rees, 1992, 1993; Rees and Mészáros, 1994; see also Narayan, *et al.*, 1992, Woosley, 1993, Usov, 1994, Katz, 1994, Paczyński and Xu, 1994, Thompson, 1994). Here we show that a dissipative unsteady wind model which is decelerated by an external medium provides a natural explanation for having a classical MeV band GRB of the usual

duration ($10^{-1} - 10^3$ s), followed by a harder GeV burst which is spread out or delayed over intervals ranging from minutes to hours, with duration comparable to the delay. The MeV burst is produced by internal shocks in the unsteady relativistic wind produced by a primary event, lasting seconds (e.g. Rees and Mészáros, 1994; see also Paczyński and Xu, 1994, where neutrino and radio emission are discussed). The GeV burst occurs when the cooled, coasting baryons from the wind run into the external interstellar medium (ISM), producing a blast wave moving ahead and a reverse shock moving back into the ejecta (e.g. Mészáros and Rees, 1993). For the baryon loading factors producing a classical MeV burst, and an external ISM of standard density, the relative delay or spread of the GeV emission respect to the BATSE MeV-band emission extends up to \sim hours.

2. Internal Shocks

In an unsteady relativistic wind of duration t_w with an energy input varying at the base on a timescale t_v , a relatively large baryon loading factor corresponding to $\eta = (L/\dot{M}c^2) \gtrsim \eta_{min} \sim 3 \times 10^1 (L_{51}/t_v)^{1/5}$ leads to internal shocks outside the wind photosphere which dissipate a sizable fraction of the bulk kinetic energy of the wind (Rees and Mészáros, 1994). If the Poynting flux provides a fraction α of the total luminosity L of the wind, the comoving magnetic field at the dissipation radius r_{dis} where the internal shocks occur is $B_{dis} \sim 10^4 \alpha^{1/2} L_{51}^{1/2} t_v^{-1} \eta_2^{-3}$ G, leading to a high radiative efficiency even for t_v as long as seconds. The internal shocks are marginally relativistic, since blobs in the wind are moving at almost the same speed. For electrons accelerated in the internal shocks to a minimum Lorentz factor $\gamma_m \sim \kappa \sim 10^2 \kappa_2$ (where $1 \lesssim \kappa \lesssim m_p/m_e$) the observed synchrotron break would come at a frequency

$$\nu_{sy,ob} \sim 10^{16} \alpha^{1/2} L_{51}^{1/2} \kappa_2^2 t_v^{-1} \eta_2^{-2} \text{ Hz} . \quad (1)$$

Inverse Compton (IC) losses would also be important, the ratio of the synchrotron photon energy to the magnetic field energy being $u_{sy}/u_B \sim \rho(\sigma_T/m_p) \gamma_m^2 f r_{dis} \eta^{-1} \sim 5 \times 10^1 L_{51} f \kappa_2^2 t_v^{-1} \eta_2^{-5}$, where $f \lesssim 1$. The IC scattered synchrotron photons would have a break frequency of

$$\nu_{IC,ob} \sim \nu_{sy,ob} \gamma_m^2 \sim 10^{20} \alpha^{1/2} L_{51}^{1/2} \kappa_2^4 t_v^{-1} \eta_2^{-2} \text{ Hz} . \quad (2)$$

This would, therefore, give a burst of duration t_w in the MeV range, detectable by BATSE at cosmological distances. The compactness parameter in the wind rest frame, depending on the energy and the radius at which the dissipation shocks occur, becomes significant for $\gtrsim 0.1 - 1$ GeV, so photo-pair creation would strongly suppress this burst over the higher part of the EGRET band.

3. External Shocks

The wind ejecta, after having produced the MeV burst through internal dissipation shocks, will continue coasting. By the time it is decelerated by encounter with the external medium at a radius $\sim 10^{17}$ cm, the wind ejecta can be treated as an ‘impulsive’ cooled fireball. (The thickness of the ‘shell’ that would have developed from an impulsive calculation with $\eta \sim 10^2$ by the time it gets out to $\sim 10^{17}$ cm, e.g. Mészáros, Laguna and Rees, 1993, is larger than the few light-seconds in the lab frame that results from the extended duration of the wind). This is compatible with the observation that the duration of the primary (MeV) burst is generally $t_b \lesssim 10^2 - 10^3$ s, while the delay and duration of the GeV burst is generally longer than this. As the ejecta is decelerated, a relativistic blast wave moves into the ISM ahead, while a reverse shock propagates into the ejecta. If the wind was dominated by the Poynting flux, the magnetic field remains in equipartition as long as the ejecta is in the wind regime, and the ratio of magnetic to rest mass energy density drops as r^{-1} thereafter. Comparing the MeV and GeV burst durations, the field would be at most a factor $\sim 10^{-1}$ below equipartition in the deceleration shocks. Alternatively, if turbulent field growth behind the shocks leads to the latter having a fraction λ of the equipartition energy, the comoving field is $B_{dec} \sim 10^1 n_0^{1/2} \eta_2 \lambda^{1/2}$ G. The blast wave would produce electrons with a minimum Lorentz factor $\gamma_m \sim \kappa \eta \sim 10^4 \kappa_2 \eta_2$. For an external medium (ISM) of density $n_{ext} \sim 1 n_0 \text{ cm}^{-3}$ the observer-frame synchrotron frequency break would be at a frequency

$$\nu_{sy,ob} \sim 10^{17} n_0^{1/2} \lambda^{1/2} \kappa_2^2 \eta_2^4 \text{ Hz} . \quad (3)$$

The observed IC scattered synchrotron photons in the blast wave zone would have a break frequency of

$$\nu_{IC,ob} \sim \nu_{sy,ob} \gamma_m^2 \sim 10^{25} n_0^{1/2} \lambda^{1/2} \kappa_2^4 \eta_2^6 \text{ Hz} . \quad (4)$$

The energy loss is dominated by the IC process, so most of the deceleration energy liberated by the external shock comes out at frequencies near (4). This is similar to the calculations for the piston model (Fig. 7) or the turbulent model (Fig. 5) of Mészáros, Rees and Papathanassiou, 1994. (However, we note that the observations may not require the MeV fluence to be low, since the BATSE trigger is activated by exceeding a certain photon count *rate*; a long ($t \gtrsim 10^3$ s) burst could in principle have significant MeV fluence without triggering BATSE). The deceleration occurs at a radius $r_{dec} \sim 5 \times 10^{16} n_0^{-1/3} E_{51}^{1/3} \eta_2^{-2/3}$ cm, and it occurs after a time delay

$$t_{del} \sim r_{dec}/(c\eta^2) \sim 5 \times 10^2 n_0^{-1/3} E_{51}^{1/3} \eta_2^{-8/3} \text{ s} . \quad (5)$$

The total duration of this burst is comparable to t_{del} if the external medium is smooth, and for a narrow range of $\eta = (L/\dot{M}c^2)$ corresponding to $t_{del} > t_w$ the external shock would produce a GeV burst delayed by t_{del} respect to the dissipation shock burst. However for a wider range of η or an inhomogeneous external medium, the beginning of the external shock burst could overlap with the later stages of the internal shock burst. If the external medium were blobby on scales $r_{blob} < r_{dec}$, time structure of order $t_{str} \sim r_{blob} c^{-1} \eta^{-2}$ would be observed. Photon statistics would also affect the time structure at GeV energies.

4. Discussion

Second generation (‘non-simple’) cosmological wind and fireball models, such as previously proposed by us, have been shown to be able to explain all the major features of classical GRBs, in particular the 0.1-100 MeV non-thermal spectrum, the total energy, duration and time structure. In this paper, we have discussed how these models also provide a natural explanation for the longer lasting GeV emission observed by EGRET in some classical GRBs.

In the model proposed here, the MeV burst is observed first, and is caused by a ‘primary event’ producing a (possibly magnetized) wind of luminosity $L \sim 10^{51} L_{51}$ ergs and duration $t_w \sim 10^{-1} - 10^3$ s. The average baryon loading may be relatively high, leading to bulk Lorentz factors $\Gamma \sim \eta = (L/Mc^2) \sim 10^2$. Intrinsic time variability of the energy input or loading factor leads to blobs or shells of slightly different Lorentz factors colliding and dissipating an appreciable fraction of the bulk kinetic energy of the wind (e.g. Rees and Mészáros, 1994; also see Paczyński, 1991, Thompson, 1994, Paczyński and Xu, 1994). A large baryon loading, and a weakly emitting quasi-thermal wind photosphere are acceptable, because the MeV burst occurs in dissipative shocks *outside* the photosphere, at the expense of the baryon bulk kinetic energy (Rees and Mészáros, 1994), in an optically thin environment leading to a nonthermal MeV spectrum. Due to the photon compactness, this burst would be suppressed above about 0.1 – 1 GeV.

A second burst arises when the wind ejecta, carrying a fraction of the initial baryon kinetic energy, has swept up an amount of external mass $M_{ext} \sim \Gamma^{-1} M_{ej}$, e.g. Mészáros and Rees, 1993. The external medium could be either the interstellar medium, or material ejected by the progenitor star (possibly in the form of a shell) in a mass loss phase prior to the GRB event. For a standard ISM of density 1/c.c. and $\eta \sim 10^3$, the duration of this burst would be of order $t_{dec} \sim t_{del} \sim$ seconds, and the spectrum extends from MeV to GeV energies (e.g. Mészáros, Rees and Papathanassiou, 1994). For higher baryon loading, e.g. $\eta \lesssim 10^2$, the duration of this burst can exceed $\gtrsim 10^3$ s and the spectrum peaks at higher energies, in the GeV range (although for such durations even a significant MeV fluence might go undetected).

Depending on the baryon loading of the ejecta and the density or blobbiness of the external medium, the time-delay of the GeV burst relative to the previous MeV burst will be in the range $5 \text{ s} \lesssim t_{del} \lesssim 5 \times 10^3 \text{ s}$, and the burst lasts some fraction of this value. For a range of η , the two bursts overlap, the GeV emission lasting longer. These bursts would be visible from cosmological distances, and would have fluxes, spectra, duration and rate of occurrence compatible with the observations. Weak X-ray and optical signatures from these bursts (Mészáros, Rees and Papathanassiou, 1994) may also be detectable by next generation omnidirectional space detectors.

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